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Design of durability test protocol for vehicular fuel cell systems operated in power-follow mode based on statistical results of on-road data

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HIGHLIGHTS

- Real on-road statistic data of an FCS operated in PF mode are presented.
- An optimized problem based on statistic values is proposed for design purposes.
- Mean changing rate and time percentage of relative load are used as key factors.
- New fuel cell durability test protocols are compared with existing ones.

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ABSTRACT

City buses using polymer electrolyte membrane (PEM) fuel cells are considered to be the most likely fuel cell vehicles to be commercialized in China. The technical specifications of the fuel cell systems (FCSs) these buses are equipped with will differ based on the powertrain configurations and vehicle control strategies, but can generally be classified into the *power-follow* and *soft-run* modes. Each mode imposes different levels of electrochemical stress on the fuel cells. Evaluating the aging behavior of fuel cell stacks under the conditions encountered in fuel cell buses requires new durability test protocols based on statistical results obtained during actual driving tests. In this study, we propose a systematic design method for fuel cell durability test protocols that correspond to the power-follow mode based on three parameters for different fuel cell load ranges. The powertrain configurations and control strategy are described herein, followed by a presentation of the statistical data for the duty cycles of FCSs in one city bus in the demonstration project. Assessment protocols are presented based on the statistical results using mathematical optimization methods, and are compared to existing protocols with respect to common factors, such as time at open circuit voltage and root-mean-square power.

1. Introduction

Polymer electrolyte membrane (PEM) fuel cells are the most favored type of fuel cell for transportation applications because they are highly efficient and do not generate greenhouse gas emissions. Fuel cell technologies have been developing rapidly in recent years, but bottlenecks still remain that hinder their commercialization. Specifically, the high cost and short working lifetimes of these units must be addressed. To understand the aging behavior of fuel cell stacks when operated under various duty cycles, it is necessary to develop test protocols that characterize the performance and durability of these devices.

Several organizations in the US and Europe have developed test procedures for this purpose. Yuan [1] reviewed the durability test protocols and pointed out that there are different kinds of test procedures for cell components (such as the electro-catalyst, catalyst support, membrane, and gas diffusion layer) and complete cells/stacks. The four typical durability test protocols for transportation applications associated with the US Department of Energy (DOE) Hydrogen Program are: 1) steady-state durability, 2) potential cycling durability, 3) start-up/shutdown cycling durability, and 4) dynamic stress test (DST) duty

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cycling. The steady-state durability tests [2] involve the operation of either a single cell or a stack under constant voltage and constant current conditions for specific time intervals. Potential cycling durability assessments [2] subject single cells to accelerated stress testing (AST) technology as a means of simulating the dynamic load in an automotive application. The start-up/shutdown cycling durability tests [3] examine the degradation of fuel cell components, as the fuel cell is subjected to start-up/shutdown cycles, while the DST duty cycle trials [4] are meant to determine the long-term durability of fuel cells when employed in vehicles. The DST protocol was designed by converting the US06 federal internal combustion engine cycle into an equivalent PEM fuel cell engine drive cycle. In addition, the US Fuel Cell Technical Team (FCTT) proposed two durability test methods [5] under wet and dry conditions.

The EU Fuel Cell Testing and Standardization Network (FCTestNet) published different fuel cell durability test protocols, such as a smooth power increases followed by power off and on-off cycling [6]. The on-off cycle is also utilized in the International Electrotechnical Commission (IEC) TS62282-7-1 standard. The New European Driving Cycle, i.e., European Commission for Europe (ECE) R15, was proposed for fuel cells based on the original R15 cycle, relating speed to power and squaring the pulses [7]. In addition, several approaches to assessing fuel cell durability were defined in the European project Fuel Cell Testing, Safety, and Quality Assurance (FCTESQA), including tests under constant current density [8] and dynamic load cycling [9]. In recent years, the European Development of PEM Fuel Cell Stack Reference Test Procedures for Industry (StackTest) project defined various testing protocols, including performance and durability testing [10]. A complete fuel cell durability test program [11] has been proposed that incorporates several test modules, including constant load durability, load cycling durability, start-stop durability, stack performance recovery, polarization curve testing, and electrochemical tests. This workflow provides a platform on the basis of which researchers can design their own testing protocols to assess the actual duty cycles of a fuel cell system (FCS).

Given the increasing number of test protocols for fuel cell durability, it is necessary to be able to compare and validate them. The Argonne National Laboratory and European Commission Directorate-General Joint Research Center previously collaborated in this regard, and Bloom [6,7] reported that the performance decline rate obtained from the four test protocols decreases in the following order: IEC > ECE R15 > DST ≈ FCTT (wet). Harms [12] studied the variability and comparability of test protocols capable of characterizing the polarization curve and voltage degradation of a cell under several different loads. Jeon [13] identified new AST test protocols for high-temperature PEM fuel cells, and compared them to a constant voltage test method while exploring changes in frequency and potential range. Meanwhile, Sharabi [14] proposed a methodology for the design of AST protocols for non-precious metal catalysts in fuel cell cathodes based on different analytical approaches, such as cyclic voltammetry, chronoamperometry and electrical impedance spectroscopy.

PEM fuel cell city buses (FCBs) are regarded as the most likely to be commercialized in China [15]. The working conditions of FCSs differ on the basis of the powertrain configurations and vehicle control strategies. The working modes of FCSs can be classified as either power-follow (PF) [16–19] or soft-run (SR) modes [29], with the aging of the cells varying in accordance with the mode applied. To evaluate the aging behavior of fuel cell stacks under FCB conditions, it is therefore necessary to design new durability test protocols based on data from actual vehicles. This paper deals with the design of fuel cell durability assessment methods for the PF mode based on the statistical data obtained from an FCB under real world conditions. This study's contribution comprises three aspects.

- It shows the real on-road statistical results of an FCS in an FCB in a demonstrational project, and reveals the effects of the PF mode on the working conditions of the FCS.
- It provides a methodology for designing test protocols based on real on-road data, including defining an optimization problem and solving it systematically. The fuel cell stack relative load is divided into several segments, and three statistical parameters for each segment are calculated, i.e., the average relative load increasing rate, the average relative load decreasing rate, and the time percentage. New test protocols are designed based on an optimization problem. The average increasing/decreasing rates in new protocols are the same as those in the statistical data, and the errors between the time percentages of each segment in new test protocols and that in the statistical data are minimized.
- Two new fuel cell durability test protocols that can evaluate the performance of an FCS operated in the PF mode are designed and compared with existing protocols.

The rest of this paper is organized as follows. The powertrain structure and control strategy associated with the PF mode are described in Section 2. The statistical results from actual vehicle trials are summarized in Section 3. Section 4 presents the process for designing the test protocols and compares them with existing assessment methods, and Section 5 presents our conclusions.

2. Powertrain configurations and control strategies

2.1. Basic powertrain structures and control strategies

The fuel economy, fuel cell durability, and dynamic performance of a fuel cell vehicle (FCV) all interact to affect the overall performance. Based on the current state of China's fuel cell industry, it is currently more practical for China to commercialize FCBs than fuel cell passenger vehicles [15]. In 2001, the Tsinghua New Energy Vehicle Team launched a research project concerning FCBs, and has since developed several generations of FCBs with different powertrain structures [16–30] in conjunction with a long-term strategic industrial partner, the SinoHytec Company. Several of these models were demonstrated at the Beijing Olympic Games in 2008 [17–20], the Shanghai Expo in 2010 [21–23], and the Singapore Youth Olympic Games (YOG) in 2010 [25]. Several have also been employed along standard bus routes in Beijing [16,30] and Shanghai. In 2015, similar technologies were utilized in a tram that was produced by Qingdao Sifang Locomotive Vehicle Co. LTD [28].

Generally speaking, the FCS in an FCB can operate in two modes, namely PF mode, in which the FCS serves as the primary power source and follows the major part of the vehicle's power requirements, and SR mode, in which the FCS functions as an auxiliary power source and corresponds to the average power requirements of the vehicle. The operational mode of a vehicular FCS is determined by several factors, including the powertrain structure, component parameters, and control strategy.

An FCB contains at least two power sources: an FCS and energy storage system (ESS), such as a lithium battery, an ultra-capacitor, or a composite system. These power sources typically operate with diverse voltage levels and a direct current converter (DCC) is usually utilized to connect them. There are also various powertrain structures that may be incorporated in an FCB, with two major types explained in Fig. 1. In Fig. 1(a), the FCS is directly connected to the electric motor control unit (MCU), which is composed of a direct current (DC) to alternating current (AC) inverter and an electronic control unit. The battery is connected to the MCU through a bi-directional DCC. In this type of powertrain, the FCS output power corresponds very closely to the dynamic requirements of the electric motor, with the charging/discharging of the battery controlled by the DCC. The FCS in this powertrain can only function in the PF mode. In Fig. 1(b), the battery is connected directly to the MCU and the output power of the FCS is controlled by a DCC. Depending on the parameters of each component and the control